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Acquisition of spatially resolved CO2 distribution in a generic train compartment

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Abstract

The presented study was conducted within the framework of the Next Generation Train project (NGT) of the German Aerospace Center (DLR). This project addresses many aspects of future high-speed trains and modern passenger and freight transport. Among others, thermal passenger comfort and energy efficiency of different ventilation systems have been analysed by implementing new ventilation and illumination concepts in a full-scale mock-up of the NGT-HST (high-speed train). With up to 20-30% of the total energy demand, the HVAC system of a train is the second-largest energy consumer during a train journey. The demand-oriented ventilation of passenger compartments is one possibility to save energy by reducing the rate of fresh air. For demand-oriented ventilation based on the CO2 distribution, energy savings between 10% and 20% were observed in previous studies in wind tunnel experiments and in operational mode. However, all the studies conducted so far are based on CO2 measurements in the exhaust air of the train compartment. Investigations of the local CO2 distribution in the compartment, i.e. possible locally increased CO2 values on individual seats, are still lacking. The objective of the present study is to investigate a novel hybrid ventilation concept in terms of CO2 distributions and CO2 discharge in a generic train mock-up (GTM). This novel concept is based on a combination of cabin displacement ventilation and a hat-rack-integrated low-momentum ventilation system. Four thermal manikins and up to 20 human subjects were placed in the GTM. The influence of different numbers of human subjects on the performance of ventilation systems in trains was studied using CO2 sensors in the vicinity of the persons as well as in the air supply and air exhausts.

Keywords: generic train laboratory, novel ventilation concepts, thermal comfort, CO2 distribution, hybrid ventilation

1 Introduction

The HVAC system of a train is the second largest energy consumer during a train journey, requiring up to 20-30% of the total energy demand. Besides new features such as heat pumps, demand-oriented ventilation is one of the main technologies used to reduce the energy demand of the HVAC system.

Demand-oriented ventilation of passenger compartments is one method to save energy by reducing the rate of fresh air. The basic idea of this concept is to supply the amount of fresh air based on the number of passengers, not on the maximum possible load. A reduction of the rate of fresh air can minimize the cooling and heating demand of the HVAC system. To maintain the required thermal conditions [1], the amount of recirculated air has to be increased while at the same time reducing the rate of fresh air.

For demand-oriented ventilation based on the CO2 distribution, energy savings of 10% were recorded in a wind tunnel experiment with a standard HVAC system in a metro in Vienna [2]. Further studies reveal a saving potential of up to 20% for modern trains operated with a fresh air regulation based on the actual demand [3]. However, all the studies conducted so far are based on CO2 measurements in the exhaust air of the train compartment. Investigations of the local CO2 distribution in the compartment, i.e. possible locally increased CO2 values on individual seats, are still lacking.

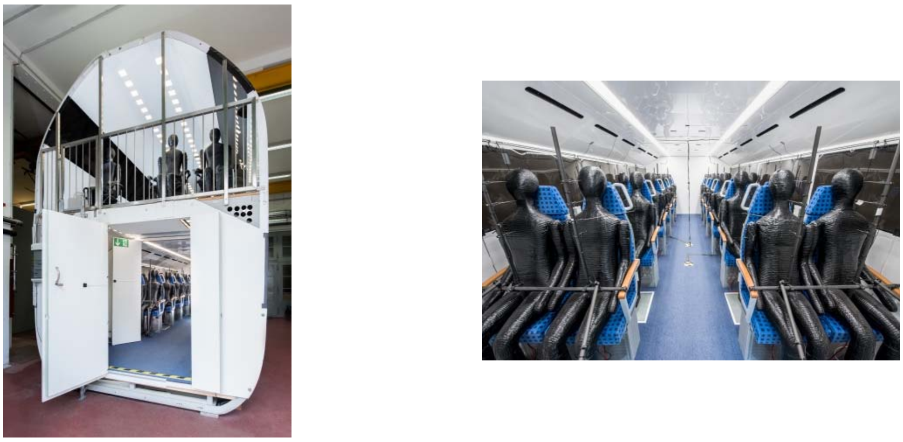

(a) (b)

Figure 1: Generic train compartment: (a) exterior view from the front, (b) view of the lower deck of the NGT-HST with thermal manikins

The objective of the present study is to investigate the spatially resolved CO2 concentration in a train compartment with a novel, hat-rack-based ventilation concept combined with cabin displacement ventilation. The investigations were carried out with 8, 12 and 20 human subjects and adjusted volume flow rates.

The study was conducted within the framework of the Next Generation Train project (NGT) [4, 5] of the German Aerospace Center (DLR). The project addresses many aspects of future high-speed trains and modern passenger and freight transport. Among others, thermal passenger comfort and energy efficiency of different ventilation systems have been analysed by implementing new ventilation and illumination concepts in a full-scale mock-up of the NGT-HST (high-speed train) [6,7,8], see Figure 1.

2 Methods

Mean compartment temperatures of 24 °C were realized for all measurements calculated using nine resistance temperature detectors (RTDs) at a height of 1.10 m across the compartment in accordance with the definition of Tim in [1]. The volume flow rate was kept constant at 9.5 l/s/PAX for all cases. More details on the positions of all probes can be found in [6, 7].

For each subject trial, four TMs were seated in the first row. The five rear rows were occupied by 8, 12 or 20 differently arranged human subjects, see black circles in Figure 4. Volume flow rates of 114 l/s, 152 l/s and 228 l/s were realized depending on the number of heat sources, i.e. passengers and TMs. Furthermore, the supply air temperature was adjusted to maintain a mean compartment temperature.

A novel, hat-rack-integrated low-momentum ventilation system (HLMV) was implemented by planar, large surface outlets, integrated in the lower part of the hat racks. Further low-momentum air outlets —attached under the seats— were used to provide cabin displacement ventilation (CDV), see Figure 2. In previous studies of ventilation in aircraft and car cabins, a volume flow rate split of 67% ceiling inlet and 33% CDV was identified as a good solution in terms of thermal comfort and energy efficiency [9, 10] and was therefore also used in the present study.

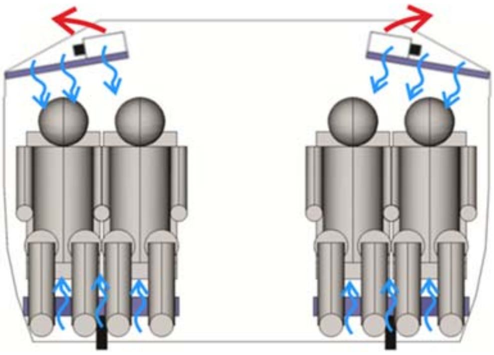


Figure 2: Sketch of the investigated hybrid ventilation scenario: A combination of hat-rack-integrated and cabin displacement ventilation

To evaluate the spatially resolved CO2 distribution in the train compartment, 24 CO2 sensors were installed at chest level (height: 1.05 m) at the back side of the backrests, i.e. at a distance of ~600 mm in front of each seat, see Figure 3. Additional CO2 sensors were mounted in the supply airflow as well as in the air exhausts. The accuracy of the CO2 sensors amounts to ±30 ppm + 3% [11] and a sample rate of 0.5 Hz was realized.

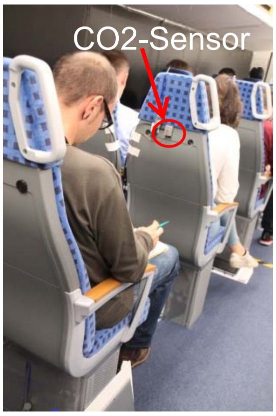


Figure 3: CO2 sensor at a distance of ~600 mm in front of the seated passenger

3 Results

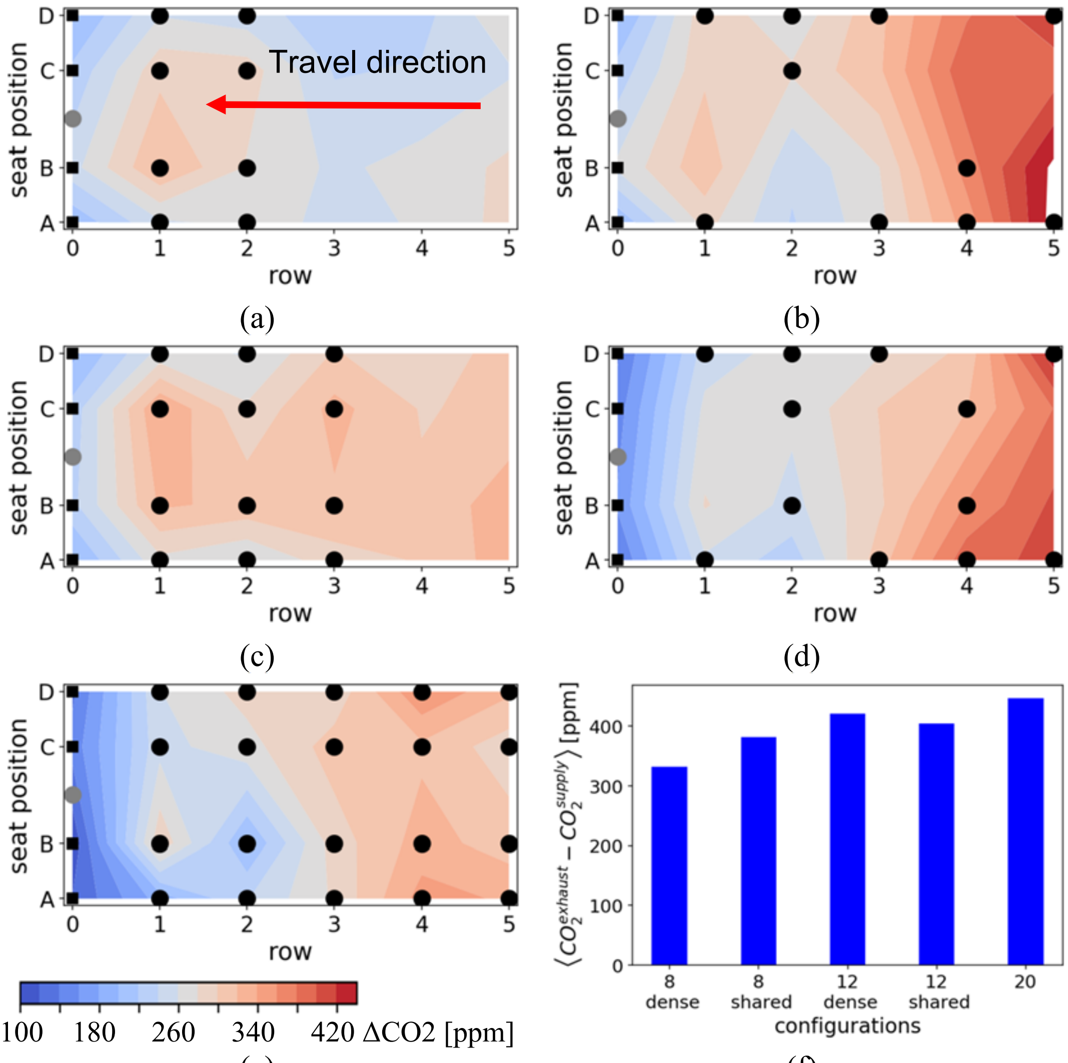
With the objective to quantify the CO2 distribution and to detect possible CO2 accumulations on individual seats, Figure 4 displays the spatially resolved CO2 distribution for the investigated cases. For the sake of comparability, the CO2 value of the supply air was subtracted. In addition to the fully occupied compartment (e), four scenarios were realized with 8 (a and b) or 12 (c and d) persons. Furthermore, for all tests, one supervisor was present in the aisle section in row 0. The parameters of all cases as well as the average, maximum, minimum and exhaust CO2 values are given in Table 1.

In the cases shown in Figure 4 (a), (c) and (e), a group of passengers was simulated by dense positioning of the human subjects. In Figure 4 (b) and (d), the “normal” case in trains was simulated with shared sitting persons.

Looking at the dense sitting configurations (a), (c) and (e), an increase in the number of passengers significantly changes the CO2 distribution in the compartment, even though it was accompanied by increased volume flow rates of the fresh air supply. For the case with just eight passengers, 8d (a), elevated CO2 values were found in the area where the passengers were actually sitting. In contrast, for twelve passengers, 12d (c), we measured higher CO2 values in the whole compartment except for row 0 where the non-breathing thermal manikins were seated. Filling the cabin with the maximum number of passengers, 20d (e), results in a strong increase in the CO2 gradient towards the rear of the compartment.

Regarding the influence of the seat configuration for a fixed number of passengers, we compare Figure 4 (a) with (b) for the case with eight passengers, and for twelve passengers (c) and (d) are compared. For the eight-passenger cases, we found that the CO2 distribution in the first three rows is not influenced when changing from the 8d

(a) to the 8s case (b). At the same time, a strong accumulation of CO2 for 8s is found in the rear part of the compartment. A similarly elevated CO2 distribution is also found for the 12s (d) case in the rear of the compartment. However, comparing 12d (c) with 12s (d) also reveals a change in the front part, highlighting the strong impact of the seating configuration on the local CO2 values.



(a) (b)

(c) (d)

(e) (f)

Figure 4: Horizontal ΔCO2 distribution ($CO_2^{seat} - CO_2^{in}$) with 8 passengers (black circles) dense (a) and shared (b), with 12 passengers dense (c) and shared (d) as well as for a completely filled compartment with 20 human subjects (e). Row 0 was equipped with four thermal manikins (black squares) and a supervisor (grey circle in the aisle). The legend below (e) applies to all distributions. (f) shows the difference of the CO2 values between exhaust and supply air for all cases.

Table 1: CO2 concentrations with reference to the supply air concentration [ppm] for all investigated cases.

Case	human subjects	Seating arrangement	Volume flow rate	CO_2^{mean}	CO_2^{max}	CO_2^{min}	$CO_2^{exhaust}$
8d	8	dense	114 l/s	258	321	197	331
8s	8	shared	114 l/s	312	449	195	382
12d	12	dense	152 l/s	287	341	194	421
12s	12	shared	152 l/s	285	435	137	404
20d	20	dense	228 l/s	253	358	104	447

Finally, the CO2 enrichment of the exhaust air ($CO_2^{seat} - CO_2^{in}$) shown in Figure 4 (f), i.e. the CO2 values typically used for the demand-oriented ventilation, will be discussed. Here, a small increase can be observed for an increasing number of passengers. However, regarding the seat configuration, no clear trends could be identified.

4 Conclusions and Contributions

We presented an experimental study with human subjects intended to analyse the CO2 concentration in a generic train compartment. The implemented ventilation concept is based on a combination of two novel systems: hat-rack-integrated low-momentum ventilation and cabin displacement ventilation.

The influence of the number of passengers and the seating configuration of the human subjects on the CO2 distribution in the train compartment was studied.

A comparison of different numbers of human subjects sitting together as a group, revealed homogeneously distributed CO2 concentrations. However, strong gradients of the CO2 values in longitudinal direction were observed for the "normal" case with shared sitting persons. The results in terms of maximum, minimum and exhaust CO2 concentration show that a single CO2 sensor in the exhaust air is not sufficient to predict the local CO2 concentrations. More probes next to the passengers to prevent increased CO2 values on scattered seats, at least when determining the set-points of the demand-oriented ventilation, are required. The present study emphasizes the need for spatially resolved measurements in order to define the optimal set-points to guarantee maximum energy savings while at the same time maintaining the air quality on all seats within the compartment.

Finally, we would like to point out that the positioning of the sensors within the compartment is also an important issue, since the probes a) should be as close as possible to the breathing zone, b) should not directly be exhaled at c) must be installed on defined positions not bothering the human test subjects.

To investigate the CO2 concentration without human subjects, a CO2 exhalation system for thermal manikins was developed at the DLR and is currently being used for first validation tests. Furthermore, an additional system for a single manikin is under construction, which will allow simulating the full breathing process including an analysis of the inhaled air. This system will have the main advantage that the air in the breathing zone is exactly analysed, making the discussion on the measurement position redundant.

Besides other air-mass flow distributions of HLMV and CDV, future research will include a comparison with state-of-the-art micro-jet ventilation. For this reason, measurements in the new DLR – DB Systemtechnik research facility DIRK (Demonstrator for innovations in passenger comfort and air conditioning) [12], which is an original ICE carriage located in a climate chamber, will be conducted.

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